Impact of mechanical stratification on the structural style of the Lublin Basin, SE Poland: results of seismic interpretation and implications for quantification of deformation within the frontal parts of thin-skinned fold-and-thrust belts

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Abstract

We demonstrate how lithological and mechanical stratification of Ediacaran–Carboniferous sedimentary package governs strain partitioning in the Lublin Basin (LB) which was incorporated in the marginal portion of the Variscan fold-and-thrust belt. Based on the geometry of seismic reflectors, the pre-Permian–Mesozoic sedimentary sequence was subdivided into two structural complexes differing in structural style. The lower one reveals forelandward-vergent imbrication, while the upper one comprises fold train, second-order deformations, and multiple local detachments. Lithological composition of the upper structural complex controlled geometry, kinematics, and position of compressional deformations in stratigraphic profile. System of foreland-vergent thrusts which links lower and upper detachment developed due to efficiency of simple shear operating in heterogeneous clastic-carbonate-evaporitic strata of the Lower–Upper Devonian age. Internal homogeneity promoted the formation of conjugate sets of thrusts in Silurian shales and Upper Devonian limestones. Structural seismic interpretation combined with sequential restoration revealed localised thickening of Devonian strata and up to 5% difference in length of Devonian horizons. This mismatch is interpreted as a manifestation of distributed shortening, including layer-parallel shortening (LPS), which operated before or synchronously to the initiation of folding. The amount of distributed strain is comparable with numbers obtained in external parts of other fold-and-thrust belts. The outcomes derived from this study may act as a benchmark for studying variability in a structural style of multilayered sequences which were incorporated in the external portion of other fold-and-thrust belts.

Keywords Layer-parallel shortening · Strain partitioning · Variscan deformation · Thin-skinned tectonics · Cross-section restoration · Lublin Basin

Introduction

External portions of fold-and-thrust belts (FTBs) have been extensively investigated, as their minor erosion and relatively low degree of deformation reduce interpretation uncertainty and offer an opportunity for studying a range of deformation processes, including layer-parallel shortening (LPS), buckling, folding and fault-related thrusting. Layer-parallel shortening starts to operate at the very early stage of deformation and may be obscured by later

processes. This mode of deformation leads to loss of a rock volume by porosity reduction, formation of pressure solution cleavage or stylolitization, and effects of this phenomenon can be observed at micro- or outcrop-scale. Later, when the compression axis is still oriented parallel to the layer boundaries, LPS is followed by buckle folding, which results in the development of a fold train due to amplification of pre-existing mechanical inhomogeneity in a rocks mass (Ramsay 1967). Buckle folds may develop both at the scale of an outcrop, or seismic profile (e.g. Konon 2006; Butler et al. 2019). Finally, anticlines and synclines may form in response to movement of material over curved fault surface, or develop due to strain accommodation in front of propagating fault (see Storti et al. 1997; Tavarnerelli 1997; Brandes and Tanner 2014 and references therein; Butler et al. 2019).

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The deformation processes that govern the structural pattern of strata in front of advancing tectonic wedge may be reduced to two end-members: thrust imbrication and distributed shortening. The former works effectively in layered rocks and favours flexural-slip folding or imbrication, while the latter operates in homogeneous beds and promotes the formation of neutral-surface folding or formation of conjugate thrusts (Ramsay 1967; Price and Cosgrove 1990). Their occurrence in a stratigraphic sequence is controlled by the lithological composition of host rocks and resultant mechanical stratification (e.g. Stockmal et al. 2001; Le Garzic et al. 2019).

In cases of underexplored FTBs, concealed beneath a younger sedimentary cover, seismic reflection data may be the only source of information on style and degree of deformation. This method, however, offers much lower resolution in comparison to observations in field outcrops, core samples, or thin sections. Therefore, cross-sections built upon seismic data are capable to unravel geometry and structural evolution of first-order deformations, and capture shortening associated with major folds and thrusts only, neglecting other smaller-scale deformations that are at or below seismic resolution (Fig. 1; Woodward et al. 1989; Saura et al. 2008; Moretti and Callot 2012; Cardozo and Brandenburg 2014; Hughes and Shaw 2014).

This study presents an attempt to relate vertical variation of the structural style resolved by seismic data to change in the lithological composition of Ediacaran–Carboniferous strata of the Lublin Basin (LB) that were involved in late Carboniferous thin-skinned folding and thrusting as the frontal part of the Variscan orogen was emplaced above the SW slope of the East European Craton (EEC, Fig. 2; Krzywiec et al. 2017a, b; Mazur et al. 2018; Kufrasa et al. 2020). The interpretation of high-resolution seismic data was carried out and combined with structural sequential restoration of both long- and short-wavelength structures to verify the admissibility of the cross-section. High-quality seismic

imaging and a low degree of deformation make this area suitable for studying the occurrence of distributed shortening and thrust imbrication within different lithological units. Mechanical stratification of rocks subjected to Variscan shortening favoured the development of multiple detachments in Ediacaran–Carboniferous strata. Variable lengths of the restored horizons have been interpreted as a result of layer-parallel shortening (LPS). The estimates of penetrative strain obtained in this study were then compared to results of LPS analyses performed in frontal parts of other FTBs.

Geological setting

SW slope of the East European Craton, where the LB is located, and within which the frontal part of the Variscan FTB is situated, was subjected to multiple geodynamic processes since Neoproterozoic–Palaeozoic. This multi-stage evolution is recorded in vertical lithological-mechanical heterogeneity of the Ediacaran–Carboniferous sedimentary infill of the LB (Fig. 3). The oldest tectonic event related to the Rodinia breakup is evidenced by a system of normal faults and related half-grabens filled with syn-kinematic clastic and volcanic rocks (Paczeńska and Poprawa 2005; Krzywiec et al. 2018a, b; Poprawa et al. 2020). The Cambrian–Ordovician post-rift thermal subsidence and ensuing development of the Peri-Tornquist Ocean are recorded by a sequence of shallow-marine mudstones, sandstones and carbonates. Vertical load exerted by docking of Avalonia to the EEC led to basement flexure and deposition of > 3 km-thick succession of the Silurian shales in a Caledonian foreland basin. Since the Early Devonian, a transition to terrigenous sedimentation is expressed by coarsening-upward sedimentary sequence attaining 2 km of the total thickness (Narkiewicz 2007). Middle–Late Devonian shallow-marine sedimentation was controlled by eustatic sea-level changes. Thin (i.e. up to 200 m) Middle Devonian strata consists of carbonate-clayey rocks that pass upward into carbonates and anhydrites. It is overlain by a much thicker (> 2 km) package of limestones, dolostones and marly limestones (Narkiewicz 2011). As a result of Late Devonian–early Carboniferous tectonic activity, the LB was split into blocks bounded by high-angle reverse faults (e.g. Krzywiec et al. 2017b; Kufrasa et al. 2018, 2019). The unconformity that developed at that time was then covered with up to 2 km-thick suite of the Mississippian–Pennsylvanian shallow-marine to fluvial clastics that contain thin limestone layers and coal seams (e.g. Waksmundzka 2013; Kozłowska and Waksmundzka 2020; Waksmundzka et al. 2021).

Prior to the onset of Permian–Mesozoic sedimentation the area of LB was subjected to major contractional deformation caused by the collision of Gondwana with the EEC (Krzywiec et al. 2017a, b; Mazur et al. 2018, 2020 and references

Fig. 1 Conceptual model of forward modelling using fault-bend folding algorithm; the amount of a horizontal shortening is equal to the difference in horizontal length of horizons in undeformed and deformed states

Fig. 2 **a** Present-day sub-Permian–Mesozoic structural framework of central Europe, except for Alpine units [compilation based on Teper (1999), Zdanowski (1999), Konon (2007), Martínez Catalán et al. (2020), Mazur et al. (2020)]; inset: generalized geological map of the

Lublin Basin (based on Waksmundzka 2010); **b** structure of the Lublin Basin and Radom-Kraśnik Block based on interpretation of PolandSPAN™ regional deep seismic reflection profile (Krzywiec et al. 2017b); see **a** for the location of the seismic line

Fig. 3 Generalized lithostratigraphy of the Phanerozoic sedimentary infill within the study area and correlation of the lithostratigraphic boundaries with seismic reflections. Rock competency is marked by column width

therein). Growth of the NE–SW-striking thin-skinned folds and thrusts detached in thick Silurian shales was accompanied by the incorporation of the LB into marginal part of Variscan tectonic wedge (Mazur et al. 2018; Kufrasa et al. 2020). Syn- and post-orogenic erosion has removed as much as up to 3 km of the Carboniferous and older strata and led to the formation of prominent and extensive angular unconformity (Krzywiec 2009; Kowalska et al. 2019; Kufrasa et al. 2019). Permian–Cretaceous cover, consisting of limestones, marls and dolostones, thickens from the NE towards the SW from 300 to 1200 m. The lateral extent of the Alpine tectonics was limited to the area located to the SW of the study area and included the Mid-Polish Trough inversion and mild reactivation of some of the Palaeozoic faults within the Radom-Kraśnik Block (RKB; Fig. 2b; Krzywiec et al. 2009). Some regional long-wavelength Jurassic and Cretaceous stages of uplift have been also documented using regional seismic data that resulted, between others, in the

reshaping of the Variscan unconformity (Krzywiec et al. 2018a, b). Discontinuous Cainozoic sedimentary cover reaches up to several meters of thickness and is composed of unconsolidated sediments: mudstones and sands.

Data and methods

Dense 2D seismic coverage of the area in the vicinity of the Lublin area enabled the construction of the time-structure maps for the main stratigraphic horizons (Fig. 4). A set of grids with a cell size equal to 250×250 m was calculated based on the interpretation of 37 roughly equally distributed archive industrial seismic profiles. Stratigraphic calibration of the seismic horizons was possible thanks to the availability of the vertical seismic profile measurements (VSP) in key boreholes that penetrated Carboniferous and/or Middle–Upper Devonian strata (Fig. 4). Time-depth relations

Fig. 4 Time-structure map of the Middle Devonian top within the study area; part of the PolandSPAN™ seismic profile used for line-length restoration and LPS analysis is marked by a thick blue line. The coordinate system used in this figure is Poland CS 1992

from these calibration wells were applied in the remaining boreholes. Wherever possible, tectonic structures were correlated between seismic profiles.

For the LPS analysis we selected a 30-km long portion of high-resolution depth-migrated PolandSPAN™ seismic profile 5100 (Krzywiec et al. 2017b), which is located in the central part of the LB, adjacent to the SW boundary of the LB with the RKB. Seismic image is characterized by high (15–20 m) vertical resolution within the Mesozoic and Upper Palaeozoic sections, achieved due to applying the following non-standard acquisition parameters: sweep frequency 2–150 Hz, sweep length 16 s, nominal fold equal to 480, and 25-m receiver/shot interval (Fig. 5; cf. Malinowski 2016). The entire PolandSPAN™ survey was time and depth (PreSDM) migrated. Below the top of Lower Devonian, notably decreased quality of seismic imaging may be observed. This is likely related to the lithological homogeneity of the Silurian–Lower Devonian sedimentary sequence composed mostly of marine mudstones and shales. Additionally, the presence of Middle Devonian evaporites (Przewodów and Giełczew Members, cf. Narkiewicz 2011) in this part of the LB hampers deeper penetration of the seismic waves.

The Phanerozoic stratigraphic column was subdivided into competent and incompetent complexes, based on their lithological composition (cf. Fig. 3). Lithostratigraphical units composed mostly of shales, mudstones or evaporites were regarded as more prone to tectonic deformation and having lower competence than packages of sandstones or carbonates (Fig. 3). The presence of strong lithological contrasts also facilitated good seismic imaging of the Middle Devonian–Carboniferous strata.

Orientation of the analysed cross-section line parallel to the direction of the late Carboniferous shortening ensured the conservation of a plane-strain state. Pin lines were placed at hinges of synclines, where minimal out-of-section material escape is expected to have occurred. From the multitude of kinematic algorithms offered by Petroleum Experts Move software, fault-bend fold was used in sequential restoration to keep bed length constant and to construct the most plausible thrust geometry based on the overlying fold shape (Suppe 1983; Connors et al. 2021). Geometry of a fault was constrained individually for each fault-related fold by forward modelling of the fold geometry in cross-section view. Once both fold's and fault's present-day geometries fitted the seismic image, they were included in restoration. A detailed

Fig. 5 Balanced geological cross-section across the southwestern segment of the Lublin Basin. Local names of structures after Tomaszczyk (2015), UKFZ Ursynów-Kazimierz Fault Zone. Zooms on areas

shown in Figs. 7, 8 and 9 are indicated by black boxes. Numbers I and II refer to main detachments

seismic interpretation permitted a selection of several key markers within the Devonian succession that were labelled a–f and used as an input for quantitative analysis (Figs. 5, 7, 8, 9, 10). The percentage of shortening for horizons a–f was measured in such a way that for each key marker, the difference between horizontal distances measured between pin lines and the restored length was multiplied by 100 and then divided by restored length. LPS has been taken into account in such a way that the marker which displays the highest percentage of shortening was considered as a reference line (marker f, Figs. 5, 10). The relative difference in length between the reference line and the remaining horizons was interpreted as an effect of LPS (Fig. 10). The cross-section has been restored to a pre-Variscan state, i.e. to the pre-Carboniferous deformation geometry (Fig. 10).

Results

Structural seismic interpretation: regional deformation pattern

The investigated PolandSPAN™ seismic profile imaged deformed sedimentary cover of the LB between the Bychawa Syncline and the Wilczopole anticline (Fig. 5). A package of non-parallel reflections occurs at depth interval occupied

by Ediacaran–Palaeozoic sedimentary rocks. Its upper portion reveals ca. 28-km wide synclinorium formed in Silurian–Carboniferous strata (Fig. 5). This structure is delimited by the Wilczopole thrust and the Ursynów-Kazimierz Fault Zone (UKFZ) to the NE and SW, respectively. Central part of the synclinorium is occupied by a 16-km wide refolded crest of the Gorzków Anticline. The flanking synclines are open, upright or gently inclined toward the foreland with amplitudes up to 1.1 km. Such a pattern is, with some degree of confidence, traceable up to approximately 8 km of depth (Fig. 5). The lower portion of the seismic profile comprises reflectors related to strata located below the Ordovician top - regionally continuous and high-amplitude seismic horizon. The geometry of reflectors within this stratigraphic interval differs from those within the overlying stratigraphic package, dipping to the southwest at an angle up to 10°. Only below the Gorzków Anticline steeper dips of seismic reflections can be identified (Fig. 5). The deepest traceable high-amplitude seismic reflector interpreted as the top of crystalline basement descends south-westwards from ca. 9–14 km below sea level (Fig. 5).

Structural analysis of seismic data permitted to distinguish two structural complexes within the Ediacaran–Carboniferous sedimentary infill. The upper one is considered as a thrust-bounded fold train developed within the Silurian–Carboniferous strata and underlain by a basal

Fig. 6 Cartoon showing conceptual model of growth of first-order folds and thrusts during late Carboniferous Variscan shortening. Numbers I and II refer to main detachments. The black box shows the position of the analysed cross-section

Fig. 7 Conjugate sets of thrusts that form fish-tail structures in Silurian strata and cause localized thickening of beds. **a** Non-interpreted seismic image, and **b** interpretation. Note the orientation of the maximum compression axis parallel to seismic reflectors

detachment in the Silurian incompetent series (I on Fig. 5). The whole stratigraphic package within this unit is hence supposed to have experienced the same amount of shortening on the regional scale. The folded beds host multiple second-order folds and thrusts well visible on seismic data. The lower complex comprises NE-vergent imbricates formed within the Ediacaran–Silurian strata. Thrust sheets are floored by a sole thrust developed in the basal part of the Ediacaran sedimentary sequence which ramps up and merges with a roof thrust (II and I on Fig. 5, respectively).

The kinematic evolution of the synclinorium is based on the assumption that the fold envelope that connects synclinal hinges approximates pre-deformational geometry of the Lower Devonian top (Fig. 5). The proposed scenario of kinematic

Fig. 8 Example of the thrust fault, which shows an upward decrease in fault displacement suggesting fault propagation in this direction. Symbols the same as in Fig. 7

evolution contains two structural units decoupled from each other by detachment I (Fig. 6). As the late Carboniferous horizontal compression commenced, the formation of the Wilczpole Anticline took place over the thrust ramp that branched off the detachment I (event 1, Fig. 6). Perhaps at the same time, the orogenic shortening caused imbrication of pre-Silurian strata above detachment II. The shortening transfer from lower to upper detachment was associated with concurrent folding of the overburden between the RKB and Wilczpole Anticline (event 2, Fig. 6). It can be supposed that events 1 and 2 occurred contemporaneously, as a similar amount of shortening is required to achieve present-day geometry of strata within the upper and lower structural units (ca. 1.5 and 2 km, respectively).

Fig. 9 Vertical differentiation of structural style: **a** the lithological transition from Lower Devonian clastics through Middle Devonian mixed clastic-carbonaceous-evaporitic sequence to Upper Devonian marly limestones facilitated simple shearing and formation of foreland-vergent thrusts deforming horizons a–b; symbols the same as in

Fig. 7 **a** uniform lithology and lack of mechanical contrasts within the Upper Devonian limestones promotes pure shear expressed by the formation of forelandward- and hinterlandward-verging thrusts between horizons d–f

Structural seismic interpretation: small-scale deformations

The analysed seismic profile reveals numerous subordinate thrusts and thrust-related folds which are concentrated in the upper structural complex that comprises ca. 3700 m thick interval of the Lower–Upper Devonian strata (Fig. 5). Shallower and deeper levels that embrace the Carboniferous and Silurian strata, respectively, do not show any signs of small-scale thrusting at seismic scale. However, with regards to the latter stratigraphic interval, the occurrence of small-scale deformations may be obscured by low signal-to-noise ratio and related inferior seismic imaging. The faulted interval corresponds to a multilayer of limestones, marls, shales and evaporites while the over- and underlying strata with no internal faulting comprise dominantly clastics (compare Fig. 3). This creates a distinct mechanical stratification of the Palaeozoic series that coincides with vertical lithological variations.

Fish-tail structures (cf. Drozdowski 1979) consist of a pair of conjugate thrust faults dipping either to the NE or SW. Faults reveal a few hundred meters of fault offset, involve 500 m thick packages of Devonian rocks, and cause localised thickening of strata (Fig. 7). The bisector of an acute angle between conjugate thrusts marks the orientation of the maximum horizontal compression axis that generated this type of structures (Hancock and Atiya 1979). In the area investigated, axes of maximum compression derived

from fish-tail structures run parallel to the seismic horizons, which suggests that the conjugate fault system developed at the early stages of deformation.

The second-order thrusts are characterized by displacements ranging from the limit of seismic resolution (i.e. 15–20 m for the PolandSPAN™ profiles) up to 1400 m. Those with larger displacements are located lower in the stratigraphic profile and offset horizons a and b (Fig. 5). The small thrusts are both foreland- and hinterland-vergent but the former dominate, in particular between markers a and c (Fig. 5). The cut-off angles are 10°–30° regardless of position within higher-order structures, which suggests their initiation in horizontal strata (e.g. Watkins et al. 2017). Upward thrusts' propagation was associated with concurrent folding in their hanging walls, as it is evidenced by the upward decrease in fault displacement and geometry of the deformed horizons (Fig. 8). It should be noticed that the highest fault displacements can be observed for the group of NE-verging thrusts in the southwestern limb of the Wilczopole Anticline (Fig. 9a), which might suggest syn-folding activity of these faults.

Within the Devonian strata, vertical differentiation of the structural style with respect to variations in lithological composition can be noticed. Conjugate sets of thrusts suggest the efficiency of distributed shortening in lithologically homogeneous strata, such as Lower Devonian mudstones or Upper Devonian carbonates (Figs. 7, 8, 9b). By contrast, mechanical heterogeneity related to the upward transition

Fig. 10 (Top) Geometry of horizons a–f restored to pre-Variscan folding and thrusting assuming bed-length conservation. Shortening was estimated for fragment located between pin lines. Note regional thinning of the Upper Devonian strata toward NE, the impact of simple shear on the geometry of the restored pin lines between horizons a–c. Non-parallel geometry of the restored horizons may point to the localised efficiency of distributed shortening. (Middle) Generalized

fragment of the cross-section shown in Fig. 5. Note position of local detachments IIIa and IIIb delimiting zone deformed by simple shear. (Bottom) A chart summarizing results of shortening calculations. Up to 5% difference in line length for horizons a–f correlates with the number of thrusts that intersect each horizon. Hence, it is inferred that thrusting-related LPS might be responsible for mismatching horizons' length

from Lower Devonian clastic sequence to Upper Devonian marly limestones favoured preferable conditions for thrust imbrication to occur (Fig. 9a). Thus, the mechanical stratification of the Lower–Upper Devonian multilayer is interpreted here as the main reason for the predominance of SW-verging thrusts in this stratigraphic interval (Figs. 9, 10).

Cross-section restoration

To quantify the amount of restorable seismic-scale strain accommodated by each horizon along with the Poland-SPAN™ seismic profile, we carried out the sequential restoration, following constant line-length and plane-strain assumptions. The top of Upper Devonian (f on Fig. 5)

was chosen as a reference horizon, as it is the shallowest seismic reflector traceable throughout the upper structural complex and displays the greatest length after restoration. Following the applied regional tectonic model, the bulk of the Variscan shortening has been accommodated in structures detached above Silurian incompetent rocks (Krzywiec et al. 2017b). The majority of thrusts resolved by seismic data within the Devonian strata reveals flat-ramp-flat geometry (Fig. 5). They link two local detachments (Fig. 10): ca. 700 m below the Lower Devonian top (IIIa), and ca. 50 m above the Middle Devonian top (IIIb). These detachment horizons are probably confined either to the presence of fine-grained strata in the Lower Devonian strata (IIIa), or mixed evaporitic-shaly intervals in the Upper Devonian

sedimentary strata (IIIb). The presence of local detachments within the Devonian succession in the area investigated has been already suggested (Kufraś et al. 2020).

The restoration of horizons a–f reveals their corrugated geometry and differences in line length (Fig. 10). Thinning of the Devonian rocks to the NE follows regional forelandward tapering of the Palaeozoic sedimentary sequence (Kufraś et al. 2020). Length of horizons was measured between the pin lines located in the hinge of Izbica and Bychawa synclines (Fig. 10). The horizon f is the shallowest one not affected by the post-Variscan erosion and hence the last that permits a reliable line-length restoration. In the ideal case, after restoration all horizons should reveal equal length. However, results of the line-length restoration, show that the shortening measured between axes of the Bychawa and Izbica synclines oscillates between 7.4 and 12% (Fig. 10). The zig-zag shape of initially straight pin lines between horizons a–c after restoration is interpreted as an effect of increased simple shearing due to competency contrasts between Lower Devonian clastic rocks and Upper Devonian limestones.

The apparent mismatch in the percentage of estimated shortening, coupled with local deviations from expected layer-cake geometry consisting of equal-length layers points to a mechanism of deformation not resolved by seismic data, which is here interpreted as LPS and/or buckling of sub-horizontal strata. Minor differences in restored lengths of markers a, b and c may result from the incorporation of the frontal portion of the hanging wall of the out-of-syncline thrust in the core of Bychawa Syncline into the procedure of shortening analysis. This out-of-syncline thrust introduces extra fragments of the horizons a–b into part of the cross-section subjected to line-length analysis (Fig. 10).

Discussion

Quality of seismic image

First, we raise the question of whether the vertical stratification of second-order thrusts and conspicuous line-length mismatch in the restored state may result from inadequate seismic acquisition and processing acquisition and rather than geology? The second-order thrusts disappear at depth and this may be attributed to the loss of seismic resolution with depth. However, high-end acquisition parameters of the PolandSPANTM survey were determined to illuminate deeper levels and hence to overcome this issue. In addition, the visibility of the small thrusts within the affected interval does not diminish with depth. The velocity model used for PolandSPANTM seismic data Pre-Stack Depth Migration was based on velocity information from numerous deep wells out of the study area and obtained depth subsurface image was

calibrated by regional well stratigraphy. Therefore, it can be concluded that our interpretation of the seismic image and cross-section restoration are not affected by seismic-data quality and processing and reflect true geological patterns. In fact, the resolution and imaging accuracy of PolandSPANTM seismic data surpass the resolution of any other seismic data acquired within the LB, including also several 3D seismic surveys (cf. Antonowicz et al. 2003; Krzywiec et al. 2017b; Kufraś et al. 2018, 2020).

Structural style of the LB as a function of mechanical stratigraphy

The results of seismic interpretation and cross-section restoration point to mechanical stratification of the Ediacaran–Carboniferous strata as a principal factor that controlled the process of deformation in the LB in the late Carboniferous. This study supports the concept of the Variscan shortening transfer from the Holy Cross Mountains Fold Belt to LB, via thrust ramp that links contemporaneously activated detachments I and II (Czarnocki 1938; Lamarche et al. 1999; Antonowicz et al. 2003; Konon 2006, 2007; Szaniawski et al. 2011; Krzywiec et al. 2017b; Mazur et al. 2018). Thrust imbrication operated effectively in lithologically and mechanically heterogeneous strata by the propagation of forelandward-vergent thrust faults. This phenomenon occurred mostly in mixed Ediacaran–Silurian clastics and carbonates, and mudstones in the upper part of the Lower Devonian which pass upward into Middle–Upper Devonian sandstones, evaporites, marls and carbonates. Thrusting in the lower structural complex seems to be facilitated by north-eastward thinning of pre-Silurian strata and shallowing of the crystalline basement that might have prevented the transfer of orogenic shortening further to NE. Numerical simulations of sheared layer bounded by weak surfaces illustrate preferable development of forethrusts (Davies and Fletcher 1990). The observed structural style of the lower structural complex and the stratigraphic interval between detachment IIIa and horizon c demonstrates this phenomenon in LB. The restored geometry of pin lines between markers a and c supports the efficiency of simple shear within this stratigraphic package (Fig. 10). This interpretation confirms the results of recent studies based on subsurface data of the structural style of the Variscan FTB developed above the SW slope of the EEC (Krzywiec et al. 2017a, b; Mazur et al. 2018; Kufraś et al. 2020).

Mechanical homogeneity of the Silurian and lower portion of Lower Devonian stratigraphic packages facilitated accommodation of Variscan contraction by distributed shortening. The strata between detachments II and IIIa occupy 50–60% of the total thickness of the Palaeozoic sedimentary sequence, so it is plausible that this weak complex controlled

formation and geometry of the fold train that builds up the synclinorium. This conclusion might be supported by the upright geometry of first-order folds.

Distributed thrusting that creates multiple small indentations of lithologically homogeneous beds and hence shortens the involved rock formations yet without nucleation of first-order thrusts or folds shall be considered a mechanism of pure shear on a formation scale operating before the slip was transferred away from the advancing backstop along with the detachments I and II. The orientation of maximum compression axes derived from observed fault geometries point to initial propagation of foreland- and hinterland-dipping thrusts which were consecutively passively folded due to long-wavelength folding. Refolded conjugate fault systems that record early phases of orogenic shortening were also reported from the more internal part of the Variscan FTB, in the late Palaeozoic Holy Cross Mountains Fold Belt, where Palaeozoic strata crop out at the surface (Konon 2006). There the development of conjugate faults due to layer-parallel compression commenced either prior to or synchronously to initiation of folding in the Upper Devonian well-bedded limestones. Evidence for analogous process in lithologically and stratigraphically comparable strata was found at seismic scale in the north-eastern limb of the Bychawa Syncline (Figs. 5, 7). Fish-tail structures described in the external portion of the Variscan orogen were reported from Ruhr Basin, which is located at the equivalent structural position as the LB (Wrede 2005).

Evidence for LPS from cross-section restoration

Lithological and mechanical stratification of a rock package undergoing compressional deformation favours strain partitioning. Experimental investigations suggest that if a multi-layered sequence embedded in homogeneous strata is subjected to compression, it deforms by imbrication, while the surrounding rocks deform mainly by penetrative strain, buckling or formation of fish-tail structures, depending on competency (Ramberg 1963; Davies and Fletcher 1990; Tavarnelli 1997; Soleimany et al. 2013). Net shortening must balance in the whole rock sequence (Ace et al. 2020). The length mismatch in restored horizons may reflect uncertainty related to flaws in structural interpretation, presence of additional detachments, or occurrence of LPS (e.g. Watkins et al. 2014; Zamora-Valcarce and Zapata 2015; Geiser 1988). The uncertainty related to ambiguous geometry of the horizons was addressed in this study by including only seismically well-imaged markers a–f into line length analysis across the restored fragment of the cross-section (Fig. 5). The presence of multiple detachments within the Ediacaran–Carboniferous strata of the LB was suggested previously both in LB (Krzywiec et al. 2017a, b; Mazur et al. 2018; Kufrasa et al. 2020), as in the Holy Cross Mountains Fold

Belt that occupies a more internal portion of Variscan FTB (Konon 2006). This study takes this concept further, in a frame of sequential restoration. The resultant model yields satisfactory fit with the seismic image and admissible geometry of the restored markers a–f if the presence of at least four detachments levels is considered (I to IIIb, Figs. 5, 10). However, even then minor differences in the percentage of calculated shortening for horizons a–f remained in the model (Fig. 10). A fault-bend folding algorithm used in structural modelling keeps bed length constant; hence the mismatch in horizons' length is interpreted as the effect of buckling or penetrative strain. Both these phenomena might have occurred prior to faulting and might have produced localized thickening of strata. It is difficult to separate them based solely on seismic data, and in this study, they are chiefly considered as distributed shortening. The difference in the percentage of shortening of markers a–e relative to reference horizon f does not exceed 5% and decreases with an increase in the number of second-order thrusts that cut each horizon (Fig. 10). Geiser (1988) concluded that, regardless of the constant bed-length assumption, restoration of purely sheared multilayer inevitably leads to line-length imbalance induced by the presence of LPS. When the restoration is completed, more competent beds should reveal longer bed length relative to incompetent intervals. In the case of the markers a–f restored in this study, pure shear is expected to operate in homogeneous, yet well-bedded Upper Devonian limestones between horizons c and f, as suggested by an inventory of structures observed in this stratigraphic interval (Figs. 7a, 9). Owing to that purely sheared horizons within an individual thrust sheet should reveal an equal amount of shortening, it is allowed to interpret up to 5% difference in length of horizons c–f as an effect of LPS. However, this number should be treated as a minimal estimate of distributed shortening, as LPS may operate continuously in front of propagating fault, as evidenced by Tavani and Storti (2011), and thus contribute to greater bed-length mismatch. This phenomenon, however, was not accounted for in this study. Localised thickening of the lowermost portion of the Upper Devonian sequence and comparable values of shortening for restored horizons a–c may suggest local occurrence of buckling which predates thrusting (Fig. 10). It should be noted that the buckles are located above future thrusts which have propagated from the Lower Devonian strata, which may point to zones of strain concentration and the kinematic link between folding and thrusting. Such interpretation is compatible with the results of structural analyses carried out both in Variscan FTB (Konon 2006) and external part of FTBs worldwide (e.g. Tavarnelli 1997).

The differences in lengths of horizons a–f in the marginal part of the Variscan orogen may be compared with the results of studies carried out in other FTBs worldwide. For example, Weil and Yonkee (2012) investigated AMS

fabric and cleavage fractures in Triassic clastics within the easternmost part of the Sevier FTB and concluded that about 5% of LPS was acquired prior to or synchronous with the growth of regional thrusting rooted in Cambrian shales. A slightly higher amount of penetrative strain, ranging between 9 and 14%, depending on the lithological composition of the deformed strata, was reported from the Glen Lyn footwall syncline located in the transition zone between the Appalachian orogen and Appalachian Plateau (Whitaker and Bartholomew 1999). Nearly identical values (10–15% of LPS) were reported from Appalachian Plateau by Ace et al. (2020) based on results of seismic interpretation combined with cross-section restoration. The LPS estimates derived from this study are, however, slightly lower than those obtained in the AMS-based study in the outer part of Pyrenean FTB (16–23%; Sans et al. 2003). This discrepancy may arise from the lithological difference between the carbonate-dominated Devonian strata in the LB and the clastic Palaeogene succession in the Pyrenees.

Summary

Newly acquired high-quality seismic profile from the central part of the LB allowed for detailed characterization of Variscan (late Carboniferous) deformations affecting Upper Palaeozoic sedimentary rocks, and relationships between small-scale and regional structures. Mechanical stratigraphy governed strain partitioning within the multilayer of Ediacaran–Carboniferous age. Ediacaran–Silurian and Lower–Upper Devonian sedimentary rocks are considered as mechanically stratified packages subjected to thrust imbrication during Variscan shortening. As a result, a series of forelandward-vergent thrusts formed to link the lower and upper detachments and keep the thrust system balanced. Stress acting on homogeneous strata was accommodated via distributed shortening expressed by conjugate sets of thrusts.

The combination of detailed structural interpretation and cross-section restoration enabled estimating the relative amount of LPS, which is expressed at the seismic scale by fish-tail structures and line-length mismatch in the restored section. Interpretation of the seismic data has revealed that short-wavelength folds and thrusts are dispersed in the Devonian succession. They are not confined to one specific detachment level, but, apparently, they utilize numerous local weak detachment levels. Cross-section balancing revealed up to a 5% difference in length of the restored horizons, which probably results from thrusting-related strain accommodation.

The estimated amount of LPS for the analysed cross-sections is comparable to those obtained from field-work-based studies carried out in other FTBs. It was

demonstrated that the LPS operates in marginal parts of orogenic wedges at early stages of shortening and could be quantifiable by detailed seismic interpretation and cross-section restoration.

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Declarations

Conflict of interest Not applicable.

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